Modeling and Simulation of Voltage Source Inverter with Voltage Drop and Its Application for Direct Torque Control of Induction Motors

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Abstract: Power electronics and electrical machines nowadays offer an extremely wide range of industrial applications. Their modeling and simulation are also a great interest to engineers. In some simulation applications, nonlinear of the power electronic devices is neglected due to its simplicity. Therefore, the performance of the control system obtained is not the same as experimental results. In this paper, a model of two-level three-phase voltage source inverter having its voltage drops is proposed. Then application to direct torque control of three-phase induction motors with the proposed model has studied. Finally, the simulation results are provided to verify the effectiveness of the proposed work.

Key words: Direct torque control, modeling and simulation, three-phase induction motor, inverter, voltage drop.

1. Introduction

Power electronics and electrical machines has been a major change in industrial applications in recent years [1]-[6], including electric, hybrid, and plug-in vehicles (EVs) in the automotive industry [7], photovoltaic (PV) [8] and wind energy conversion systems (WECS) in the renewable energy industry, [9] or high voltage direct current (HVDC) and flexible ac transmission systems (FACTS) [10]. Specially, two-level three-phase voltage source inverter (VSI) is considered as a mature technology and becoming an industrial standard for the demand for energy saving. Accordingly, application to VSI fed three-phase induction motors (IM) can be considered a valid solution for energy saving because these motors are a simple and rugged electrical machine with adaptation to several load situations, and low cost acquisition and maintenance.

Direct torque control (DTC) is one of the advanced control schemes for ac drives [4], [11]. It is characterized by simple control algorithm, easy digital implementation and robust operation. In recent years, direct torque control (DTC) strategies of induction motor (IM) drives have been widely implemented in industrial variable speed applications which it is one of the advanced control schemes for ac drives. Introduced in the middle of the 1980s, it is characterized by simple control algorithm, easy digital implementation and robust operation. Since then, several investigations carried out in order to improve the performance of the original DTC strategy. The major focused features are the uncontrolled switching

frequency of the inverter and the high torque ripple resulting from the use of flux and torque hysteresis controllers [4].

(a) An ideal voltage source inverter. (b) A real voltage source inverter with IGBTs/Diodes.

Fig. 1. Voltage source inverter.

In some simulation applications, mainly the voltage drops of the power electronic devices (e.g. IGBTs, Diodes etc.) are neglected due to its simplicity [3]. Therefore, the performance of the control system obtained is not the same as the experimental results [12]. In order to overcome this, the model of a non-ideal two-level three-phase VSI (real VSI) is proposed in the paper. Then application to direct torque control of three-phase induction motors with the proposed model are studied.

The paper is structured so that a model of an idea inverter is reviewed in Section 2. Section 3 proposes a real inverter. A general description of the induction motor model is showed in Section 4. The direct torque control is discussed in Section 5, the simulation results are showed in Section 6, and conclusions are drawn in Section 7.

2. Model of an Idea Inverter

Fig. 1(a) shows an ideal two-level three-phase voltage source inverter (VSI) with six idealized switches, S_1 to S_6 and a dc constant voltage source V_{dc} connecting a three-phase load. This inverter having the power devices is considered as ideal switches which there are no snubbers and gate drive circuits. Each phase leg of the VSI is represented by a “switch” that has three input terminals as follow:

$$v_{as} = v_{a0} - v_{s0} \quad (1)$$

$$v_{bs} = v_{b0} - v_{s0} \quad (2)$$

$$v_{cs} = v_{c0} - v_{s0} \quad (3)$$

where v_{as} , v_{bs} , and v_{cs} are the phase-to-neutral voltages.

$$v_{as} + v_{bs} + v_{cs} = v_{a0} + v_{b0} + v_{c0} - 3v_{s0} \quad (4)$$

Assuming that the system is balanced operation

$$v_{as} + v_{bs} + v_{cs} = 0 \quad (5)$$

$$v_{s0} = \frac{v_{a0} + v_{b0} + v_{c0}}{3} \quad (6)$$

$$v_{as} = \frac{2v_{a0} - v_{b0} - v_{c0}}{3} \quad (7)$$

$$v_{bs} = \frac{2v_{b0} - v_{c0} - v_{a0}}{3} \quad (8)$$

$$v_{cs} = \frac{2v_{c0} - v_{a0} - v_{b0}}{3} \quad (9)$$

Equations (7)-(9) are model of an ideal VSI.

Fig. 2. MATLAB/Simulink model for an ideal VSI [3].

Fig. 2 shows MATLAB/Simulink model for an ideal VSI, including six idealized switches.

3. Model of Real Inverter

The power electronic devices (e.g. IGBTs, Diodes etc.) are nonlinear. It is well-known that the voltages drop of the power electronic devices causes distorted motor voltage and increasing motor current harmonic distortion, and reduction of the fundamental voltage/current component. This model includes the voltage drops in the IGBT switching devices and the freewheeling diodes which is shown in Fig. 1 (b). It is known that the instantaneous voltage drops of one converter leg presented by a switching device or a freewheeling diode can be represented by an on-state forward voltage drop connected in series with an on-state resistance. Thus, this voltage drop of one inverter leg can be calculated by Equation (10) [12]

$$v_{drop} = v_f + R_{on}i \quad (10)$$

where v_f is the on-state forward voltage drop and R_{on} is the on-state resistance.

In addition, the inverter voltage drop on one inverter leg depends on both its instantaneous switching state and its relevant phase current direction. There are four cases considered as follows:

Case 1: if the current i_{as} flows to load ($i_{as} > 0$) and the ($S_1=1$) as shown in Fig. 3(a) then the terminal voltage v_{ao} is defined by can be calculated as

$$v_{ao} = V_{dc} - v_i = V_{dc} - v_{fi} - R_{oni} |i_{as}| \quad (11)$$

where v_i is the voltage drop of the IGBT; v_{fi} and R_{oni} are the forward drop of IGBT, on-state resistance of IGBT, respectively.

Case 2: if ($i_{as} < 0$) and the ($S_1=1$) as shown in Fig. 3(b) then the terminal voltage v_{ao} is defined by

$$v_{ao} = V_{dc} + v_d = V_{dc} + v_{fd} + R_{ond} |i_{as}| \quad (12)$$

where v_d is the voltage drop of the Diode; v_{fd} and R_{ond} are the forward drop of Diode, on-state resistance of Diode, respectively.

Case 3: if the current i_{as} flows to load ($i_{as} < 0$) and the ($S_1=0$) as shown in Fig. 3(c) then the terminal voltage v_{ao} is defined by

$$v_{ao} = v_i = v_{fi} + R_{oni} |i_{as}| \quad (13)$$

Case 4: if the current i_{as} flows to load ($i_{as} > 0$) and the ($S_1 = 0$) as shown in Fig. 3(d) then the terminal voltage v_{ao} is defined by

$$v_{ao} = -v_d = -v_{fd} - R_{ond} |i_{as}| \quad (14)$$

Equations (7)-(9) and Equations (11)-(14) verify a mathematical model of a VSC having its voltage drop.

Fig. 3. Analysis of each phase leg for a proposed VSI.

(a) MATLAB/Simulink model on one real VSI leg.

(b) MATLAB/Simulink model on three real VSI legs

Fig. 4. Analysis MATLAB/Simulink model of a proposed VSI.

Base on Equations (7)-(9) and Equations (11)-(14), a MATLAB/Simulink model on one real VSI leg is developed as shown in Fig. 4(a). Also, Fig. 4(b) shows a MATLAB/Simulink model of VSI having its voltage drops.

4. Mathematical Model of Three-Phase Induction Motors

4.1. Voltage Equations

The voltage equations with respect to machine variables may be expressed as

$$\mathbf{v}_s = R_s \mathbf{i}_s + \frac{d\lambda_s}{dt} + j\omega \lambda_s \quad (15)$$

$$\mathbf{v}_r = R_r \mathbf{i}_r + \frac{d\lambda_r}{dt} + j(\omega - \omega_r) \lambda_r \quad (16)$$

where $\mathbf{v}_s$ and $\mathbf{v}_r$ are the stator and rotor voltage vectors, respectively; $\mathbf{i}_s$ and $\mathbf{i}_r$ are the stator and rotor current vectors, respectively; λ_s and λ_r are the stator and rotor flux linkage vectors, respectively; R_s and R_r are the stator and rotor winding resistance, respectively.

4.2. Flux-Linkage Equations

The flux-linkage equations may be expressed as

$$\lambda_s = L_s \mathbf{i}_s + L_m \mathbf{i}_r \quad (17)$$

$$\lambda_r = L_r \mathbf{i}_r + L_m \mathbf{i}_s \quad (18)$$

where $L_s = L_{ls} + L_m$ represents the stator self-inductance; $L_r = L_{lr} + L_m$ represents the rotor self-inductance; L_{ls} and L_{lr} are the stator and rotor leakage inductances, respectively; and L_m is the magnetizing inductance. Note that all the rotor parameters and variables, such as R_r , L_{lr} , $\mathbf{i}_r$, $\mathbf{i}_r$ and, in the above questions are referred to the stator side.

4.3. Electromagnetic Torque Equation

The electromagnetic torque equation, given

$$T_e = \frac{3P}{2} \frac{L_m}{\sigma L_s L_r} \lambda_s \lambda_r \sin \theta_T \quad (19)$$

where P is the number of pole pairs.

4.4. Motion Equation

The motion equation, given

$$\frac{d\omega_r}{dt} = \frac{P}{J} (T_e - T_L) \quad (20)$$

where J is the total moment of inertia of the rotor and load, P is the number of pole pairs, T_L is the load torque

5. Direct Torque Control

DTC is an advanced control method originally developed for induction machine drives, which is a good solution for medium and high power electrical drive applications. This method has advantage in terms of

ease of implementation and less computation time. The DTC is characterized by the absence of PI regulators, coordinate transformations, current regulators, and PWM signals generators. However, the DTC presents some disadvantages that can be summarized in the following points such as difficulty to control torque and flux at very low speed, variable switching frequency behavior, high noise level at low speed, lack of direct current control. The principle and implementation of DTC are follows as

5.1. Principle of Direct Torque Control

The electromagnetic torque is given by the following equation

$$T_e = \frac{3P}{2} \frac{L_m}{\sigma L_s L_r} \lambda_s \lambda_r \sin \theta_r \quad (21)$$

The dynamic of the stator flux vector is governed by the stator voltage equation expressed in the stationary reference frame, as follows

$$\frac{d\lambda_s}{dt} = v_s - R_s i_s \quad (22)$$

Neglecting the voltage drop $R_s i_s$ across the stator resistance

$$\frac{d\lambda_s}{dt} = v_s \quad (23)$$

The torque comparator as

$$dT_e = \begin{cases} 1, \text{for } T_e^* - T_e > \frac{\Delta T_e}{2} \\ 0, \text{for } -\frac{\Delta T_e}{2} < T_e^* - T_e < \frac{\Delta T_e}{2} \\ -1, \text{for } T_e^* - T_e < -\frac{\Delta T_e}{2} \end{cases} \quad (24)$$

The flux comparator as

$$d|\varphi_s| = \begin{cases} 1, \text{for } |\varphi_s^*| - |\varphi_s| > \frac{\Delta \varphi}{2} \\ 0, \text{for } |\varphi_s^*| - |\varphi_s| < -\frac{\Delta \varphi}{2} \end{cases} \quad (25)$$

5.2. Stator Flux and Torque Calculation

The stator voltage α component estimation equation to estimate the stator flux as follows

$$v_{\alpha s} = R_s i_{\alpha s} + \frac{d\varphi_{\alpha s}}{dt} \quad (26)$$

The stator flux α component estimation equation to estimate the stator flux as follows

$$\varphi_{\alpha s} = \int (v_{\alpha s} - R_s i_{\alpha s}) dt \quad (27)$$

The stator voltage β component estimation equation to estimate the stator flux as follows

$$v_{\beta s} = R_s i_{\beta s} + \frac{d\varphi_{\beta s}}{dt} \quad (28)$$

The stator flux β component estimation equation to estimate the stator flux as follows

$$\varphi_{\beta s} = \int (v_{\beta s} - R_s i_{\beta s}) dt \quad (29)$$

The electromagnetic torque estimation equation is given by the following equation

$$T_e = \frac{3p}{2} (\varphi_{as} i_{\beta s} - \varphi_{\beta s} i_{as}) \quad (30)$$

Fig. 5. DTC scheme for an induction motor drive.

Table 1. Motor Parameters

Parameter	Symbol	Value	Unit
Rated stator line-line voltage	V_n	380	V
Rated speed	n_r	1480	rpm
Number of pole pairs	P	2	
Rated stator frequency	f	50	Hz
Rated torque	T_n	26.5	N.m
Stator winding resistance	R_s	1.37	Ω
Rotor winding resistance	R_r	1.1	Ω
Stator leakage inductance	L_{ls}	0.1459	H
Rotor leakage inductance	L_{lr}	0.149	H
Magnetizing inductance	L_m	0.141	H
Moment of inertia	J	0.1	kg.m ²

Table 2. Parameters of Proposed Inverter

Parameter	Symbol	Value	Unit
Forward drop of IGBT	v_{fi}	1.8	V
On-state resistance of IGBT	R_{oni}	0.0694	Ω
Forward drop of Diode	v_{fd}	1.75	V
On-state resistance of Diode	R_{odi}	0.0694	Ω

The magnitude of stator flux linkage vector is given by

$$|\varphi_s| = \sqrt{\varphi_{as}^2 + \varphi_{\beta s}^2} \quad (31)$$

The angular position of stator flux linkage vector is given by

$$\theta_{\varphi s} = \arctan \frac{\varphi_{\beta s}}{\varphi_{as}} \quad (32)$$

5.3. Control System

The block diagram of the DTC control system for the IM is shown in Fig. 5. This block includes the DTC controller, a VSI, and a IM.

(a) v_{as}

(b) v_{bs}

(c) v_{cs}

(d) Three-phase currents

(e) Flux

(f) Electromagnetic torque

Fig. 6. Performance analysis of proposed VSI.

6. Simulated Studies

In order to fully study the effect of the forward voltages drop of the power electronic devices in the power converter on the performance of a control system, comparative simulation studies were carried out by using MATLAB/Simulink. The simulation method uses Runge-Kutta algorithm with step size of 0.001ms. First, the MATLAB/Simulink model of IM is built based on its mathematical model which is shown in the section 4.

(a) v_{as}

(b) v_{bs}

(c) v_{cs}

(d) Three-phase currents

(e) Flux

(f) Electromagnetic torque

Fig. 7. Performance analysis of ideal VSI.

The parameters of the motor are given in Table 1. In the simulation, the stator flux linkage reference is set to 0.9889 Wb. Also, the Electromagnetic torque reference is set to 2.65 N.m. The DC bus voltage of inverter is set to 300 V. Table 2 shows parameters of proposed inverter.

The proposed inverter is compared to the ideal inverter in terms of its ability to DTC of IM by evaluating:

- (a) The phase A output voltage waveform;
- (b) The phase B output voltage waveform;
- (c) The phase C output voltage waveform;
- (d) The phase A, phase B, and phase C output voltage waveforms;
- (e) Magnitude of stator flux linkage vector;
- (f) Electromagnetic torque.

Fig. 6 shows a set of simulation waveforms for application DTC of IM with proposed inverter. Fig. 6(a) illustrates the proposed inverter output voltage waveform in phase A. Fig 6(b) illustrates the proposed inverter output voltage waveform in phase B. Fig. 6(c) illustrates the proposed inverter output voltage waveform in phase C. It is obvious from Fig. 6(a), Fig. 6(b), and Fig. 6(c) that reduction the voltage components.

Similarly, Fig. 7 shows a set of simulation waveforms for the ideal inverter study. Fig. 7(a) illustrates the proposed inverter output voltage waveform in phase A. Fig. 7(b) illustrates the proposed inverter output voltage waveform in phase B. Fig. 7(c) illustrates the proposed inverter output voltage waveform in phase C. It is obvious from Fig. 7 that no reduction of the voltage components.

As can be seen in Figs. 6(f) and 7(f) that a higher electromagnetic torque ripple under the proposed inverter when compared to the ideal inverter case.

These simulation results confirm that the mathematical model of the VSI having its voltage drops is correct.

7. Conclusion

In this paper, a model of two-level three-phase voltage source inverter having its voltage drops is proposed. Then applying to direct torque control of three-phase induction motors with the proposed model has studied. The proposal can be easily expanded to other applications.

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